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AN OPTIMIZATION AND PERFORMANCE ANALYSIS OF INDUSTRIAL SCALE HEAT EXCHANGER USING GENETIC ALGORITHM & ASPENTECH OPTIMIZER TOOL

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ABSTRACT

In this study, the Genetic Algorithm (GA) has been used to investigate the optimum operating conditions and the total annual cost of heat exchangers. It is postulated to use a COM server in order to make communication easier between Genetic Algorithm (GA) toolbox of MATLAB and Aspen HYSYS® software. The reason of choosing the proposed algorithm is to improve heat exchanger performance. This has been achieved by minimizing the total annual cost of shell and tube heat exchanger, then implementing the output values of the decision variables into the Aspen EDR® software. The calculated cost of the GA - EDR case is compared with different scenario of the same shell and tube heat exchanger. It can be seen that the cost for the GA-EDR case is less than the cost of the studied heat exchanger by 37.5% and 29.2% respectively for a new and optimized cases.

KEYWORDS: Heat Exchanger, Total Annual Cost, Optimization, Genetic Algorithm (GA), Aspen HYSYS® & Aspen EDR®

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Original Article

INTRODUCTION

Energy conservation is one of the most important research topics in the field of oil, gas, and petrochemical industry. Among various types of equipment used in these plants, heat exchangers have recently received remarkable importance. This is due to its effective conserve energy efficiency. In order to improve the performance of heat exchanger, various optimization techniques and softwares (Genetic algorithm and AspenTech) are used in this study. Accordingly Aspen HYSYS® and Aspen EDR® software's are used for optimization and performance evaluation of different types of the heat exchangers. This research has focused on heat exchangers in the preheat train of "Basrah Refinery" to investigate the most optimum operating conditions that provide maximum energy saving coupled with cost reduction. Basically the preheat train is simulated and optimized using Aspen Hysys® software and its petroleum refining functionality, as shown in Figure 1. These optimized preheat exchanger then have been exported to Aspen EDR® for further rigorous simulation, sizing, and analysis. Pressure drops through the shell and tube sides of each heat exchanger along the preheat train have been chosen at their maximum values to provide more specific results. TEMA types of all heat exchangers along the preheat train have been used as indicated in as-built design defined available in the datasheets. Some factors from as-builts exchangers TEMA datasheet have been used to simulate the new heat exchanger designs, i.e. fouling resistance, tube length, size, and pattern configuration, allocation of hot and cold stream, and pressure drops through both

shell and tube sides. GAs are adaptive techniques that can be used to solve problems through investigating and optimizing [1]. This technique can be classified as one of the evolutionary algorithms that can rely on the imitation of the Darwin's work for natural selection and survival of the strongest [2]. The basic steps of how to give a simple cycle in GA are as follows:

- Creating of an initial population.
- Estimating of each chromosome.
- Electing the best.
- Generating a new population of a chromosome by applying a series of operators: Selection, Crossover, and Mutation.
- Selecting survivors.
- Stopping criteria, here the cycle will be stopped when it reaches to the best solution.

Genetic algorithm includes unique and distinguished features such as no assumptions about the function to be optimized are needed. Basically, GAs optimizes the tradeoff between exploring new points in the search space and exploiting the information discovered. Only objective function or fitness information is needed for GAs to find an optimal solution, this makes them competent to traditional optimization techniques that require derivatives or other auxiliary knowledge [3]. In the meanwhile, these features were encouraging in the application of the genetic algorithm (GA) on optimization and performance analysis of heat exchangers. It's applied on one of the heat exchangers in "preheat train" which is called crude oil/kerosene exchanger and item number (E01). In this work, the literature review of research projects, which have been conducted in the field of GA, has been summarized as follows: **Xie et al.** (2008) applied GA to optimize plate-fin compact heat exchanger. Furthermore, they generalize their work and developed an optimization procedure to find the minimum volume and/or annual cost, and pressure drop of heat exchangers, respectively, based on the e-NTU and GA technique. Within their study, they presented a case study to show the optimized results by the proposed method that confirmed procedures

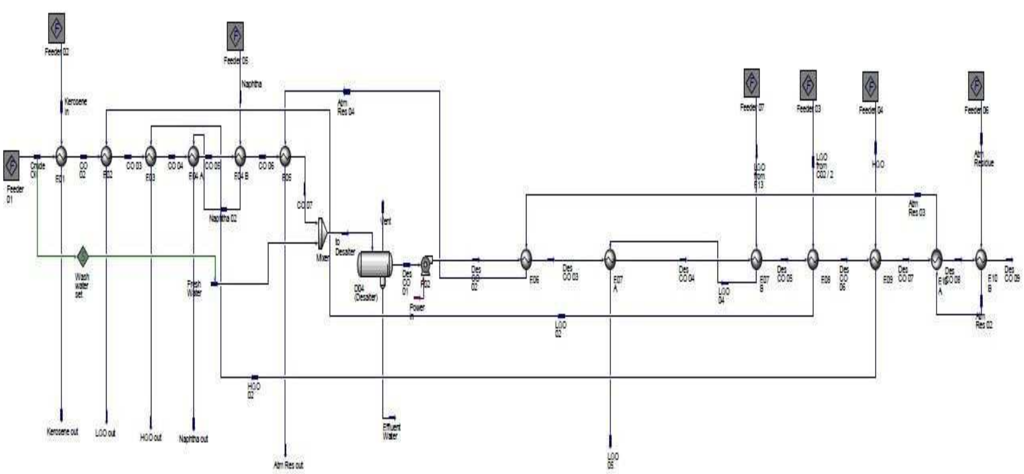

Figure 1: Simulation of Basrah Refinery's Preheat Train by Aspen HYSYS®

Applicability [4]. **Rajasekara et al.** (2010) applied the Modified Genetic Algorithm (MGA) to develop and test a model for optimization of the early design phases of shell-and-Tube Heat Exchangers. Such MGA heat exchanger models effectively help designers to make precise decisions at the early phases of design. This helps effectively when there is a shortage of available information in the design process [5]. **Iqbal et al.** (2014) studied a finned double-pipe heat exchanger with triangular fins. They aimed at finding optimal configurations of the finned annulus. They considered laminar and forced convection on the exchanger's shell-side. They employed GA as the optimizer and finite element method as the flow solver [6]. **Sadeghzadeh et al.** (2015) used a multi-objective genetic algorithm to investigate the optimal design of a Finned Shell-and-Tube Heat Exchanger (FSTHE). Their objective functions were as: to maximize heat transfer operation, and minimize total cost. Throughout the study, they considered nine decision design variables, these are: tube arrangement, tube pitch ratio, number of tubes, tube length, tube diameter, fin height, fin thickness, number of fins per unit length and baffle spacing ratio [7]. **Yadav et al.** (2016) studied the design optimization of compact heat exchangers. They considered that the task of optimization, itself, may be considered as a design process in which any possible candidates will be analysed and evaluated based on the requirements. They concluded that GA technique may be used for optimization of geometrical parameters of heat exchangers to obtain optimal results [8].

OPTIMIZATION MODEL OF SHELL AND TUBE HEAT EXCHANGER

The general model that was carried out on the tubular heat exchanger for optimization, has been implemented on the shell and tube heat exchanger. With some changes that include the following [9]:

The same objective function for optimization is the total annual cost which is represented by the following equation, the utility cost for this case study will be cancelled:

$$C_T = A_o K_f C_{Ao} + A_o E_i H_y C_i + A_o E_o H_y C_o \tag{1}$$

The only constraint for the objective function is derived from the overall heat balance which is related to the rate equation:

$$q = w_u c_{pu}(t_2 - t_1) = w'c'_p(t'_1 - t'_2) = U_o A_o \Delta t_{lm} \tag{2}$$

$$\frac{\Delta t_{lm}}{q} = \frac{1}{A_o U_o} = \frac{1}{A_o}\left(\frac{D_o}{D_i h_i} + \frac{1}{h_o} + R_d\right) \tag{3}$$

And as follows:

$$\frac{(\Delta t_2 - \Delta t_1)}{q \ln(\Delta t_2/\Delta t_1)} - \frac{1}{A_o}\left(\frac{D_o}{D_i h_i} + \frac{1}{h_o} + R_d\right) = 0 \tag{4}$$

Where,

$$R_d = \frac{D_o}{k_w D_{lm}} + \frac{D_o}{D_i h_{di}} + \frac{1}{h_{do}} \tag{5}$$

The power loss inside and outside tubes for shell and tube heat exchanger are derived as follows:

Power Loss Inside Tubes

$$E_i = \frac{\Delta p_i w_i}{\rho_i A_o} = \frac{\Delta p_i G_i \frac{1}{4}\pi D_i^2}{\rho_i \pi D_o L n} = \frac{\Delta p_i G_i D_i^2}{4\rho_i D_o L n}. \tag{6}$$

Pressure Drop Inside Tube

$$\Delta p_i = \frac{2 f_i G_i^2 Ln}{\rho D_o} \tag{7}$$

Fanning friction factor for turbulent flow in tubes is given by:

$$f_i = \frac{0.046}{(D_i G_i/\mu_i)^{0.2}} \tag{8}$$

Film heat transfer coefficient inside tubes:

$$\frac{h_i D_i}{k_i} = 0.023\left(\frac{D_i G_i}{\mu_i}\right)^{0.8}\left(\frac{C_{pi}\mu_i}{k_i}\right)^{\frac{1}{3}}\left(\frac{\mu_i}{\mu_{wi}}\right)^{0.14} \tag{9}$$

Rearranging Equation. (9)

$$G_i = \left[\left(\frac{h_i D_i^{0.2}\mu_i^{0.8}}{0.023 k_i}\right)\left(\frac{k_i}{C_{pi}\mu_i}\right)^{\frac{1}{3}}\left(\frac{\mu_{wi}}{\mu_i}\right)^{0.14}\right]^{1.25} \tag{10}$$

Also,

$$G_i = \frac{4W_i.4n_p}{\pi.D_i^2 N_t} \tag{11}$$

Substituting Equation. (10) and Equation. (7) after substituting f_i, into Equation. (6) and simplifying to result:

$$E_i = \frac{h_i^{3.5} B_i D_i^{1.5} \mu_i^{1.83}\left(\frac{\mu_{wi}}{\mu_i}\right)^{0.63}}{(1.02)(0.023)^{2.5} g_c D_o \rho_i^2 k_i^{2.33} C_{pi}^{1.17}} \tag{12}$$

Where B_i is a correction factor to account for friction due to sudden contraction, sudden expansion, and reversal of flow direction, dimensionless. g_c represents the conversion factor in Newton's law of motion.

The same procedure can be used to derive the power loss equation inside the tube. This power losses equation is then applied for the shell except that using of hydraulic equivalent diameter. The final equation is calculated based on a triangular tube pitch:

$$D_{eqv} = 8 * \frac{\frac{\sqrt{3}}{4}.P_t^2 - \frac{\pi D_o^2}{8}}{\pi D_o} \tag{13}$$

Power Loss Outside Tubes

$$E_o = \frac{\Delta P_o G_o S_o}{\pi.L.N_t.D_o \rho_o} \tag{14}$$

$$S_o = \frac{N_C D_C\, L}{n_b} \tag{15}$$

Where: S_o = shell-side free-flow area across shell axis.

N_C = number of clearances between tubes for flow of shell-side fluid across the shell axis.

D_C= clearance between tubes to give smallest free area across shell axis.

n_b = number of baffle spaces = number of baffles + 1.

The Pressure Drop in the Shell Side is Calculated as

$$\Delta P_o = \frac{2B_o f_o N_r G_o^2}{g_c \rho_o} \tag{16}$$

Where B_o correction factor to account for friction due to reversal of flow direction, recrossing of tubes, and variation in cross section, dimensionless. N_r represents the number of rows of tubes across which shell fluid flows, for turbulent flow across tubes.

$$f_o = b_o \left(\frac{D_o G_o}{\mu_o}\right)^{-0.15} \tag{17}$$

For staggered tubes,

$$b_o = 0.23 + \frac{0.11}{(x_T - 1)^{1.08}} \tag{18}$$

Where x_T= ratio of pitch normalized transverse to flow to tube diameter.

And:

$$\left(\frac{h_o D_e}{k_o}\right) = \frac{a_o}{F_s}\left(\frac{D_e G_o}{\mu_o}\right)^{0.8}\left(\frac{C_{po}\mu_o}{k_o}\right)^{\frac{1}{3}} \tag{19}$$

$$G_o = \left[\left(\frac{h_o D_e^{0.4}\mu_o^{0.6} F_s}{a_o k_o}\right)\left(\frac{k_o}{C_{po}\mu_o}\right)^{\frac{1}{3}}\right]^{1.67} \tag{20}$$

Where a_o = 0.33 for staggered tubes.

Also,

$$G_o = \frac{W_o . P_t}{D_S . B . C} \tag{21}$$

Thus,

$$E_o = h_o^{4.75} \frac{2B_o N_r N_C b_o D_C D_o^{0.75} F_s^{4.75} \mu_o^{1.42}}{\pi n_b N_T a_o^{4.75} g_c \rho_o^2 k_o^{3.1} C_{po}^{1.58}} \tag{22}$$

It is clear that:

$$A_o = \frac{Q}{U_D . F . LMTD} \tag{23}$$

And:

$$L_T = \frac{A_o}{\pi D_o N_T} \tag{24}$$

OPTIMIZATION STRATEGY AND PROBLEM DEFINITION

The objective function (C_T), the total annual cost, is affected by the surface area, the power requirement for pumping the fluids in the inner tubes and the outer shell. In our work, the hot kerosene flows in the shell side while cold crude oil flows inside the tubes of the heat exchanger. Kerosene flows with the mass flowrate of 39710kg/hr at a pressure of 635.8kPa. The inlet and outlet temperatures of kerosene are 191 °C and 76°C, respectively. Crude oil flows with mass the flowrate of 397540 kg/hr at a pressure of 2016kPa. The inlet and outlet temperatures of crude oil are 25°C and 40°C,

respectively. At the optimum conditions, flow in the tube and shell side is turbulent. The following mentioned parameter is defined and used without being changed along the optimization problem [9]:

- Installation is 15% of the purchased cost.
- Annual fixed charges, including maintenance, are 20% of the installed cost.
- Purchased cost of shell and tube heat exchanger with carbon steel for the outer shell and inner tubes is about 260 $/m2.
- Electrical cost is 0.04 $/kWh.
- Fouling coefficient for kerosene is 2500 W/m2. K
- Fouling coefficient for crude is 1666.67 W/m2. K
- The exchanger operates 7000 hr/yr.

The selected decision variables with their upper and lower bounds are as follow:

- Number of tube passes (NP) where $1 < NP < 8$
- Tube inside diameter (D_i) where $0.005 < D_i < 0.012$ (m)
- Tube outside diameter (D_o) where $0.008 < D_o < 0.022$ (m)
- Number of tubes (NT) where $180 < NT < 550$
- Shell inside diameter (IDS) where $0.5 < IDS < 1.5$ (m)
- Baffle spacing (b) where $0.1 < b < 0.3$ (m)
- Number of baffles (n_b) where $1 < n_b < 4$
- Tube pitch (P_t) where $0.023 < P_t < 0.04$ (m)

Additional assumptions are used as follow:

$B_i = 1$; $B_o = n_b+1$; $F_s = 1.3$ and N_C. $N_r/N_T = 1$

Prior to use the genetic algorithm toolbox of MATLAB, genetic operators should be defined. These operators are defined as:

- Number of generations = 50.
- Population size = 50.
- Population type = double vector.
- Fitness scaling = Rank.
- Selection = Tournament (Size of tournament (N) =4).
- Crossover = Constraint dependent.

- Mutation = Constraint dependent.
- Stopping criteria = Function tolerance (1E-3)

SOLUTION METHODOLOGY FOR OPTIMIZATION OF CASE STUDY

The optimization procedure is applied after writing a user defined function (C_T) in MATLAB as shown in the Figure 2. One of the questions in this work is how to calculate the physical properties for each generated solution in the search space. One of the used techniques is to extract the values of these properties from thermophysical database such as Aspen database which is attached with the aspen HYSYS® simulation software. This was achieved by establishing a Component Object Model (COM) server, which enabled the communication between MATLAB and Aspen HYSYS®. COM is a platform-independent, distributed, object-oriented system for creating binary software components that can interact [10]. In other words, Aspen HYSYS® and MATLAB are able to exchange data through COM. The latter transfer data between the two programs in binary form regardless the programming language which was used to build any one of the two software's.

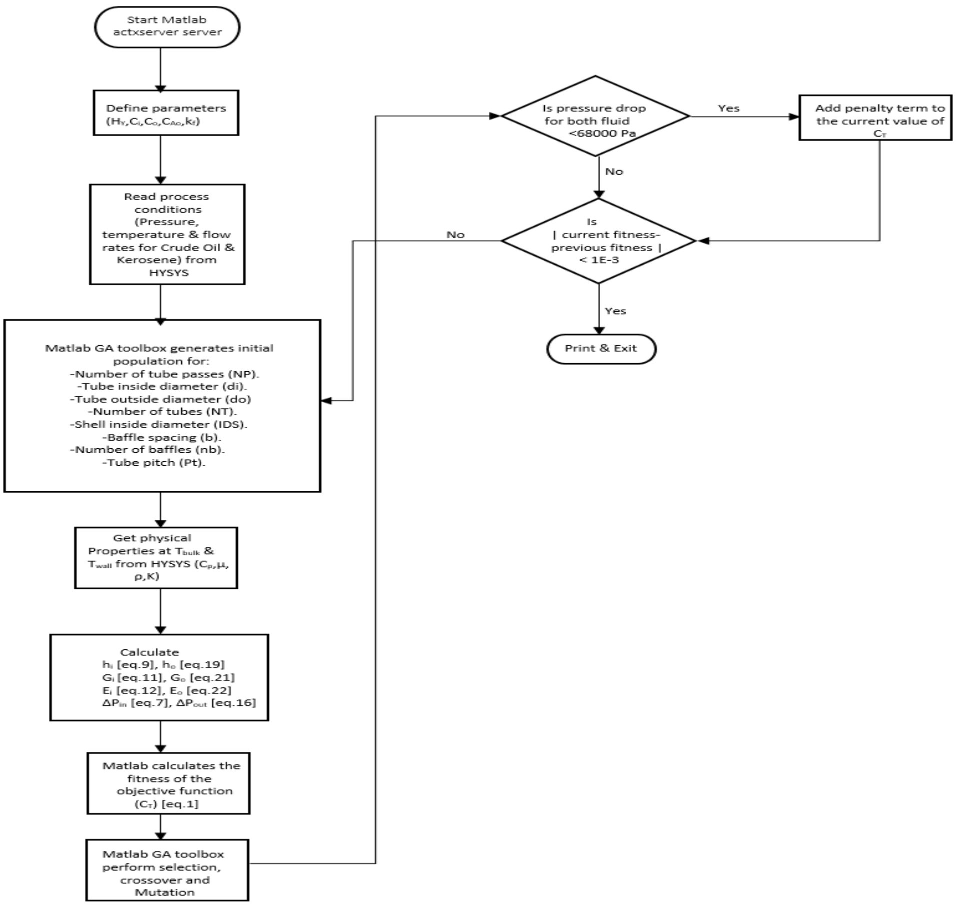

Figure 2: Optimization Algorithm for Shell and Tube Heat Exchanger

RESULTS AND DISCUSSIONS

The shell and tube heat exchanger under study is used to heat crude oil in Crude Oil Distillation unit at the South Refineries Company. By using the optimization procedure, the total annual cost for shell and tube heat exchanger at new,

optimum and GA-EDR design, is minimized as shown in Table 1.

Table 1: Results for Shell and Tube Heat Exchanger Optimization using Genetic Algorithm

Heat Exchanger: (E01) *Kerosene / Crude Oil TEMA* Type: AES					
Item		**Design**			
		As-built	**New**	**Optimum**	**GA-EDR**
Shell-side stream: Kerosene	Inlet temperature, °C	191	191	191	191
	Outlet temperature, °C	76	73.51	73.51	73.51
Tube-side stream: Crude oil	Inlet temperature, °C	25	25	25	25
	Outlet temperature, °C	40	39.98	40	39.97
Mass flow rates, Kg/hr	Shell-side stream	39710	39710	39710	39710
	Tube-side stream	397540	397540	397540	397540
Exchanger layout	Shell diameter, mm	750	750.89	711.2	500
	Tube Length, mm	4500	4500	4267.2	2812
	No. of tubes	510	485	432	391
	Tube diameter / pitch, mm	20 / 26	20 / 26	20 / 26	18/23
	Area of heat transfer, m^2	144	127.6	107.6	55.5
Thermal analysis	Heat duty, MM KCal/hr	2.694	2.626	2.626	3.054
	Overall heat transfer coefficient (service), Kcal/hr.m^2. °C	217	231.8	274.9	533.2
	ΔP_{ss}, kg/cm^2	0.087	0.056	0.038	0.12
	ΔP_{ts}, kg/cm^2	0.884	0.60	0.70	0.80
Baffles	Type	Segmental	Segmental	Segmental	Segmental
	Orientation	Horizontal	Horizontal	Horizontal	Horizontal
	Baffle spacing, mm	151	151	203.2	100
	% Cut	22	20.62	24.15	21
Cost estimation	Aspen EDR's calculated cost, $	-	59,969	52,546	36,658

The output values for the decision variables obtained by GA optimization for shell and tube heat exchanger are summarizes in Table 2.

Table 2: Optimization Results for Decision Variables using Genetic Algorithm

Decision Variables	**GA Optimized, 8 Decision Variables**
Number of tube passes x (1)	2
Inside diameter of tubes x (2), m	0.012
outside diameter of tubes x (3), m	0.018
Number of tubes x (4)	391
Inside diameter of shell x (5), m	0.5
Baffle spacing x (6), m	0.1
Number of shell baffles x (7)	4
Tube pitch x (8), m	0.023

As it can be extracted from Figure 3, the minimum total annual cost of the GA-EDR design for the shell and tube is achieved after 90 generations with a minimum value of 3668 USD/year. In order to test the results obtained from GA optimization, the values of the decision variables mentioned in Table 2 are implemented in Aspen EDR®. It should be noted that the cost of heat exchanger in Aspen EDR® is calculated based on the materials cost and the operating cost plus to that the labour cost [11]. The cost of labour can be defined as the sum of all wages paid to employees that are defined by

the hourly rate of work. The results from GA-EDR are compared with the as-built, new and optimized designs of the crude oil heater against kerosene. The results shown in Table 1 show that the cost obtained from the GA-EDR is lower than all the new and optimized cases by 37.5% and 29.2% respectively.

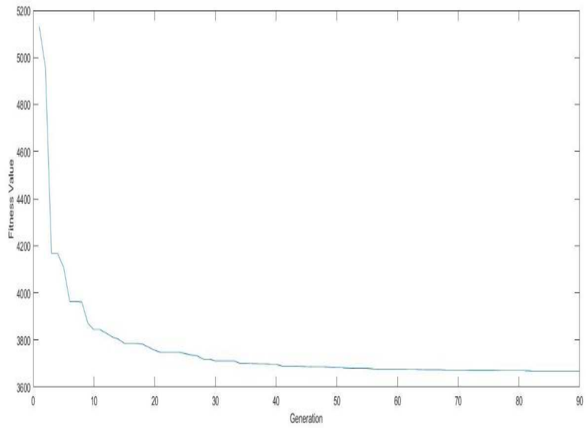

Figure 3: Convergence Curve of GA Optimization for Shell and Tube Heat Exchanger

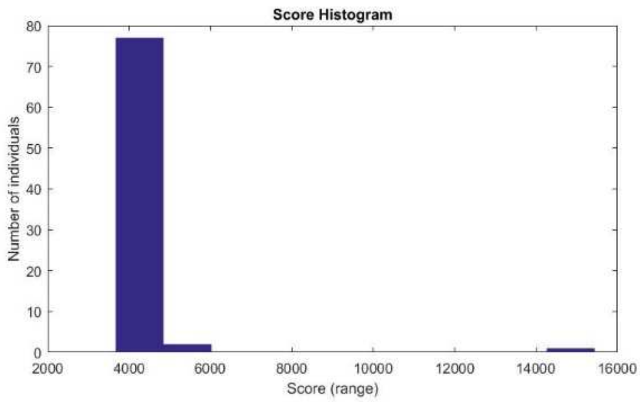

Figure 4: Score Histogram for Shell and Tube Optimization Using GA

In Figure 4, the number individuals versus their scores are illustrated showing that most of the individuals achieved scores around 4000 where the optimum value lies. This also confirms the steep convergence curve in Figure 3.

CONCLUSIONS

The optimization process can be determined in two steps, firstly, improving the design and improving operating conditions through providing the optimum temperature, pressure, mass flow rates, etc., Secondly, by using the following optimization tools: Aspen Tech optimizer tool and MATLAB genetic algorithm toolbox.

To optimize the performance of heat exchangers operated in the targeted industrial facilities, Aspen HYSYS® software has played an effective role in improving the operating conditions of the studied heat exchangers. In contrast, Aspen EDR® software was used to improve the mechanical and thermal design of those heat exchangers. If we have to take cost figures for all heat exchangers in the Crude oil Distillation unit as shown in Table 3, the economic saving improvement of the process heat exchangers about 40.63%. After applying the genetic algorithm, a comparison between

new, optimized and GA-EDR design was investigated. The cost of the GA - EDR case showed an optimization behaviour compared to the cost of the studied heat exchanger at a new and optimized case.

Table 3: The Minimum Annual Cost for Shell and Tube Heat Exchanger

Unit	Total Cost, $		Saving Money, %
	Unoptimized Designs	Optimized Designs	
Crude Oil Distillation	2,470,596	1,466,798	40.63

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REFERENCES

1. *Ribeiro, Jose and Treleaven, Philip, Genetic Algorithm Programming Environments, London: University College (1994).*
2. *Juan S. Muñoz1, Raúl Valencia and Cesar Nieto, "COMSOL and MATLAB® Integration to Optimize Heat Exchangers Using Genetic Algorithms Technique," Boston, 2008.*
3. *Manish C. Tayal, Yan Fu. and Urmila M. Diwekar, "Optimal Design of Heat Exchangers: A Genetic Algorithm Framework," Ind. Eng. Chem. Res., vol. 38, no. 2, pp. 456-467, 1999.*
4. *G.N. Xie, B. Sunden and Q.W. Wang, "Optimization of compact heat exchangers by a genetic algorithm," ELSEVIER, PP. 895–906, 2008.*
5. *S.Rajasekaran1 and Dr.T.Kannadasan2, "Optimization of Shell and Tube Heat Exchangers Using modified Genetic Algorithm," International Journal of Control and Automation, vol. 3, no. 4, 2010.*
6. *Z. Iqbal, M. Ishaq and K. S. Syed, "Optimization of Laminar Convection on the Shell-Side of Double Pipe with Triangular Fins," Arab J SciEng, vol. 39, pp. 2307–2321, 2014.*
7. *Humbe, A. B., Deshmukh, P. A., & Kadam, M. S. (2014). The Review Of Articulated R12 Robot And Its Industrial Applications. International Journal Of Research In Engineering & Technology IJRET, 2(2), 113-118.*
8. *HeidarS adeghzadeh, Mehdi Aliehyaei and Marc A. Rosen 3, "Optimization of a Finned Shell and Tube Heat Exchanger Using a Multi-Objective Optimization Genetic Algorithm," Sustainability, vol. 7, pp. 11679-11695, 2015.*
9. *Mona S. Yadav and S.A. Giri, "Genetic Algorithm Based Optimization of Compact Heat Exchangers: A Review," International Advanced Research Journal in Science, Engineering and Technology, vol. 3, issue. 5, 2016.*
10. *Max S. Peters and Klaus D. Timmerhaus, PLANT DESIGN AND ECONOMICS FOR CHEMICAL ENGINEERS: McGraw-Hill, Inc., United States, 1991.*
11. *"COM, Threading Models and apartments," [Online]. Available:*

    https://msdn.microsoft.com/en-us/library/windows/desktop/ms680573%28v=vs.85%29.aspx?f=255&MSPPError=-2147217396
12. *Aspen Exchanger Design and Rating V9 software, help.*

NOMENCLATURE

English Symbols

A_o Outside surface area of heat transfer, m^2

a_o Constant, a = 0.33, dimensionless

B Baffle spacing, m

b_o Constant in Equation. (18) for evaluating shell-side friction factor, dimensionless

B_i Correction factor to account for friction due to sudden contraction, sudden expansion, and reversal of flow direction, dimensionless

B_o Correction factor to account for friction due to reversal of flow direction, recrossing of tubes, and variation in cross section, dimensionless

C Tube clearance, m

c_p Heat capacity, W/kg.°C

CA_o Installed cost of heat exchanger per unit of outside-tube heat transfer area, $/m^2

C_i Cost of supplying 1 J to pump the fluid through the inside of the tubes, $/J

C_o Cost of supplying 1 J to pump the fluid through the outside of the tubes, $/J

C_T Total annual variable cost for heat exchanger and its operation, $/year

D Diameter, m

Ds Inside shell diameter, m

D_{eqv} Hydraulic equivalent diameter based on tube pitch, m

D_C Clearance between tubes to give smallest free area across shell axis, m

E Power loss per unit of outside-tube heat transfer area, W/m^2

f Fanning friction factor, dimensionless

F Correction factor, dimensionless

F_s Safety factor, dimensionless

g_c Conversion factor in Newton's law of motion, m/s^2

G Mass velocity, kg/s.m^2

h Film coefficient of heat transfer, W/m^2.K

H_y Hours of operation per year, hr/year

k Thermal conductivity, W/m.K

K_f Annual fixed charges including maintenance, expressed as a fraction of initial cost for the completely

installed unit, dimensionless

L Length of one tube, m

L_T Total length of heat exchanger, m

n Number of tube passes, dimensionless

n_b Number of baffle spaces, number of baffles + 1, dimensionless

N_c Number of clearances between tubes for flow of shell-side fluid across shell axis, dimensionless

N_r Number of rows of tubes across which shell fluid flows, dimensionless

N_T Total number of tubes in exchanger, dimensionless

p Pressure, pa

P_t Tube pitch, m

q Rate of heat transfer, W

R_d Combined resistance of tube wall and scaling or dirt, $m^2.K/W$

S_o Shell-side free-flow area across shell axis, m^2

t Temperature of utility fluid , ℃

t' Temperature of process fluid, ℃

U Overall heat transfer coefficient, subscript d indicates that a dirt or fouling factor is included, subscript o indicates based on outside area and fouling factor include, $W/m^2.K$

w Mass flow, prime refers to process fluid, kg/s

Greek Symbols

Δ Δ_t designate temperature-difference driving force,

ΔP_{ss} Shell-side Pressure drop, kg/cm^2

ΔP_{ts} Tube-side Pressure drop, kg/cm^2

μ Absolute viscosity, kg/m.s

ρ Density, kg/m^3

Ψ_i,Ψ_o Dimensional factors for evaluations of E_i and E_o

x_T Ratio of pitch transverse to flow to tube diameter, dimensionless

Subscript

d Scaling or dirt

i Inside pipe or tube

lm Log mean

o	Outside pipe or tube
u	Utility fluid
w	wall

Abbreviations

COM	Component Object Model
e-NTU	Number of Transfer Units method
EDR	Exchanger Design and Rating
GA	Genetic Algorithm
HYSYS	Hydrocarbon Simulation system
MGA	Modified Genetic Algorithm